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Interactions between Local Oxygen Deficiencies and Heterotrophic Microbial Processes in the Elbe Estuary*

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With 6 Figures and one Table

Key words: Dissolved oxygen, nitrification, heterotrophic processes, phytoplankton, degradation, Elbe Estuary

Abstract

Between 1991 and 1994 an interdisciplinary research group studied the factors which control the formation and position of local oxygen depletion areas within the longitudinal freshwater profile of the Elbe Estuary. The investigations were based on the assumption that microbial oxygen consumption was important and that the quantities of the organic and inorganic substances which are metabolized by heterotrophic processes differ significantly along a longitudinal profile. To test this assumption, during different times of the year longitudinal concentration profiles were obtained for parameters characterizing the physico-chemical conditions, and the abundances of bacteria and phytoplankton were counted. Results indicated that the oxygen regime in the warmer seasons was controlled by microbial O_2 consumption, coupled to the degradation of freshly transported organic substances from upstream which mainly consisted of phytoplankton. Laboratory studies on the types and rates of heterotrophic processes in seston revealed that after formation of aggregates the oxygen consumption increased up to 1000 fold. Two independent processes could be identified to control this increase within the seston aggregates: the decay of fresh phytoplankton and the formation of low molecular weight DOC under low oxygen concentrations.

Combining the results from both laboratory and field studies, we conlude that a decrease in the oxygen concentration in the Elbe Estuary caused an increase in heterotrophic processes in the seston material which again produced a further decrease of the oxygen concentration in the open water. This autocatalytic effect might also be important in cycling of organic matter and nutrients from particulate suspended matter in other aquatic systems.

Introduction

Since the beginning of this century local oxygen deficiencies during early summer have been described for the Elbe Estuary. Typical for the Elbe is the occurrence of an oxygen minimum zone at the end of spring in the region of Glückstadt (Fig. 1). This zone moves further upstream during the next few months and reaches its final position downstream from Hamburg Harbour during early summer, when oxygen concentrations of below 3 mg O_2 l^{-1} are detected. Under these conditions oxygen might become critical for fish and benthic organisms. In the literature, oxygen deficiencies have been described for a number of different estuaries. In the Schelde Estuary anoxic conditions occur in the region along the longitudinal profile where phytoplankton dies due to the increase in salinity (BODERIE et al. 1993). At the Loire an oxygen minimum is regularly observed in the turbidity zone (THOUVENIN 1992). In the Chanjiang Estuary low oxygen concentrations occur at the outer edge of a freshwater lense lying above marine water, which is characterized by a salinity of 26% and low particulate matter (10 mg l^{-1}). These conditions, including high concentrations of plant nutrients, favour phytoplankton growth in the surface water. During settling the phytoplankton dies in deeper layers and becomes degraded by microbial processes coupled to oxygen consumption. Oxygen thereby decreases to concentrations below 3 mg l^{-1} (TIAN et al. 1993). For the Chesapeake Bay different processes have been described to produce oxygen deficiencies (OFFICER et al. 1984). These start during February and May when the water column becomes stratified by a temperature gradient. Within 2 to 3 months anoxic conditions are reached below a depth of 8 m. An increase in oxygen occurs after the mixing of the whole water column during September/October. The organic substrate for the oxygen respiration in the depth of the Chesapeake Bay derived from the phytoplankton blooms produced during summer of the year before its consumption. Because during sum-

* This paper is dedicated to Prof. Dr. HARTMUT KAUSCH on the occasion of his 60[th] birthday.

mer anoxic conditions occur in deeper waters and during winter temperature inhibits microbial degradation sedimenting phytoplankton is conserved near the bottom until early spring. Then, with increasing temperature and sufficient oxygen the material is degraded producing a depletion of the oxygen concentrations.

Recent studies showed that the availability of phytoplankton for heterotrophic microbial processes causes oxygen deficiency in the Elbe Estuary (KERNER et al. 1995). Until then, the oxygen minimum below Hamburg Harbour was explained by nitrification of ammonium transported into the Elbe Estuary at high concentrations from upstream regions. In the present paper the long-term changes of the environmental conditions that cause oxygen deficiencies in the Elbe Estuary are studied. In field studies along longitudinal profiles and stationary sites changes in the availability of substrates for autotrophic and heterotrophic processes in the Elbe Estuary were monitored. In laboratory experiments on seston aggregates, the effect of a depletion of oxygen on particulate microbial degradation processes was studied. Both laboratory and field experiments are discussed with respect to possible strategies to improve water quality in estuaries.

Material and Methods

Study site

The Elbe Estuary has a length of about 142 km with the freshwater section (salinity < 0.5‰) reaching from the weir at Geesthacht (km 590) to about Glückstadt (km 670) (Fig. 1). The particulate organic matter (POM) entering the estuary from upstream originates predominantly from riverine production, as indicated by an average $\delta^{13}C$ value of about −28‰ (KERNER & KROGMANN 1994). Most of the POM is phytoplankton dominated by diatoms, which accounted for 90% and 71% of the total algal cell numbers in spring and summer, respectively, between 1989 and 1993 (ARGE 1982–95). Likewise, in March 1995, Chl *a*:fucoxanthin ratios of between 2.2 and 2.8 were found at km 610 of the Elbe Estuary, indicative of diatoms being the predominant phytoplankton present (F. EDELKRAUT, pers. comm.).

During downstream transport the suspended particulate matter (SPM) passes through Hamburg Harbour (km 625), which acts as a sink for sedimenting particles. This not only affects the SPM from upstream but also the sedimenting particles, which are transported upstream during flood tide (DYER 1988). The region downstream from km 610 is a net-heterotrophic system because primary production is limited by light, and the increase in water depth to about 10 m and reduced vertical mixing might not allow even a self-sustaining photosynthesis (WOFSY 1983; WOLFSTEIN & KIES 1995).

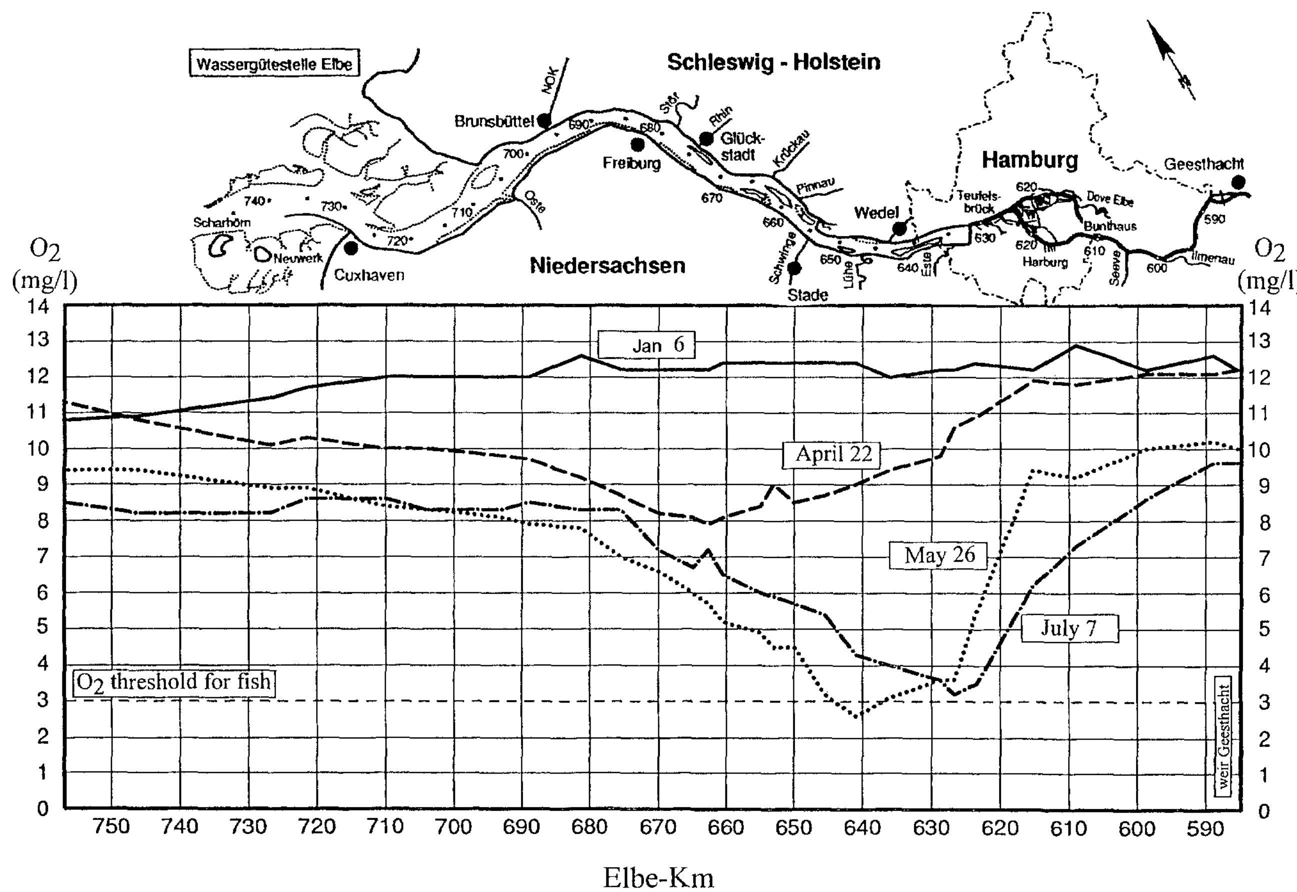

Fig. 1. Map of the Elbe Estuary (Germany) and changes in the oxygen concentrations along the longitudinal profile during the course of the year 1993 (data from ARGE 1982–95).

Table 1. Analytical methods used both in the laboratory and field studies on the Elbe Estuary.

Parameter	Method	Reference
Oxygen	Clark-type electrode	KERNER (1993)
Ammonium, nitrate, nitrite	Flow-injection-analysis	GRASSHOFF et al. (1983)
Dissolved oxocarboxylic acids	HPLC after derivatization, UV detection	EDELKRAUT & BROCKMANN (1990)
Dissolved carbonyl compounds	HPLC after derivatization, UV detection	EDELKRAUT & BROCKMANN (1990)
Fe(II), Mn(III), S(II)	Electrochemical analyses	KERNER (1993)
Biological oxygen demand (BOD)	Oxygen consumption in suspensions	KLAGES (1995)
POC, C:N	Dry combustion in an elemental analyser	GRASSHOFF et al. (1983)
Chlorophyll *a*	HPLC with fluorescence detection	DAEMEN (1986)

Sampling

At km 628.8 continuous measurements of O_2 and weekly measurements of NH_4 and biological oxygen demand (BOD) were done between 1982 and 1994 by the Wassergütestelle Elbe (ARGE 1982–1995). This station is representative for the region below Hamburg Harbour. Changes in phytoplankton biomass between 1982 and 1995 are shown from monthly measurements at km 589, a station marking the upper end of the Estuary. For field experiments on 25 and 26 of May 1993 ten stations were sampled in an upstream direction between km 680 and 609 during water runoff (Fig. 1). At each station 20 liters of water were taken from 2 m below the surface at mid-stream using a horizontally orientated sampler (Hydrobios, Kiel, Germany). For the laboratory studies in summer 1994 and 1995, about 20 l of estuarine water were collected with a clean bucket from the surface during ebb tide at Teufelsbrück (km 630) downstream from Hamburg Harbour (Fig. 1). In both laboratory and field studies along the longitudinal profile, the suspended particulate matter was fractionated and concentrated from the water samples by a sedimentation method described in detail by KERNER & KROGMANN (1994). A specially shaped funnel was used which allowed the separation of suspended particles capable of sedimentation at a rate of $\geq$0.02 cm s^{-1} (sed. PM) from the permanently suspended particles (susp. PM) of $\leq$0.1 mm (DYER 1986). Because most of the free-living zooplankton does not settle using this method, the sedimenting fraction was depleted of these, and degradation processes were restricted to the particle-associated microbial community. Chemical analyses of dissolved and particulate substances were performed as described below. Additionally, microscopic studies including bacterial cell numbers and phytoplankton composition were performed during the field studies and results were published elsewhere (BÖTTCHER et al. 1995; SCHÄFER & HARMS 1995; WOLFSTEIN & KIES 1995).

Laboratory experiments

A device was used to study heterotrophic microbial processes within a seston layer similar to those in seston aggregates of the open water (KERNER & GRAMM 1995). The device consists of an incubation cell, in which sedimenting seston forms a layer of about 1mm in depth on a porous membrane of about 60 µm thickness. Above and below the seston layer was a chamber which was continuously exchanged with water of defined composition. By controlling the concentrations of inorganic terminal electron acceptors, the redox conditions in the seston layer were controlled. During the experiments, water samples were collected three times a day from the constantly mixed water columns over and under the seston layer. In the samples thus obtained the consumption of inorganic electron acceptors (O_2, NO_3^-, Mn^{3+}, Fe^{3+}, SO_4^{2-}) was determined to quantify the microbial respiration processes. Furthermore, the hydrazones of C_1 to C_4 oxocarboxylic acids and carbonyl compounds were measured to observe the production of low molecular dissolved organic substances (DOC) during defined environmental conditions. After 56 or 75 and 98–100 hours of incubation the particulate matter was completely resuspended, removed and prepared for the determination of chemical composition.

Analytical and mathematical methods

The analytical methods used both during laboratory and field experiments are summarized in Table 1 and described in detail by KERNER & GRAMM (1995) and KERNER et al. (1995). The potential photosynthetic activity along the longitudinal profile was calculated from photoautotrophic production and consumption processes within the water column taking into account the light conditions covered by depth and SPM concentrations (FAST 1993).

Results and Discussion

Long term changes in the Elbe Estuary

After the german reunion in 1989 many industries in the former German Democratic Republic were closed and the purification of municipal and industrial sewage was intensified. Both resulted in a reduction of the pollution of the middle Elbe (ADAMS et al. 1996). Despite of this, oxygen deficiencies occurred during early summer after 1989 similar to the years before (Fig. 2a). The oxygen regime improved only with respect to anaerobic conditions which regularly occurred until 1989. Thereafter, concentrations rarely decreased below 2 mg l^{-1}. Even at low temperatures during winter, oxygen consumption processes prevented a saturation with the air with a deficit of about 20% in the 1980's that reduced to about 10% in the 1990's.

The positive tendencies in the oxygen regime were coupled to a marked decrease in the BOD reflecting that the amount of substrates degradable in oxygen consuming processes was continuously reduced in the Elbe Estuary. The annual budged of oxygen consumption computed from the

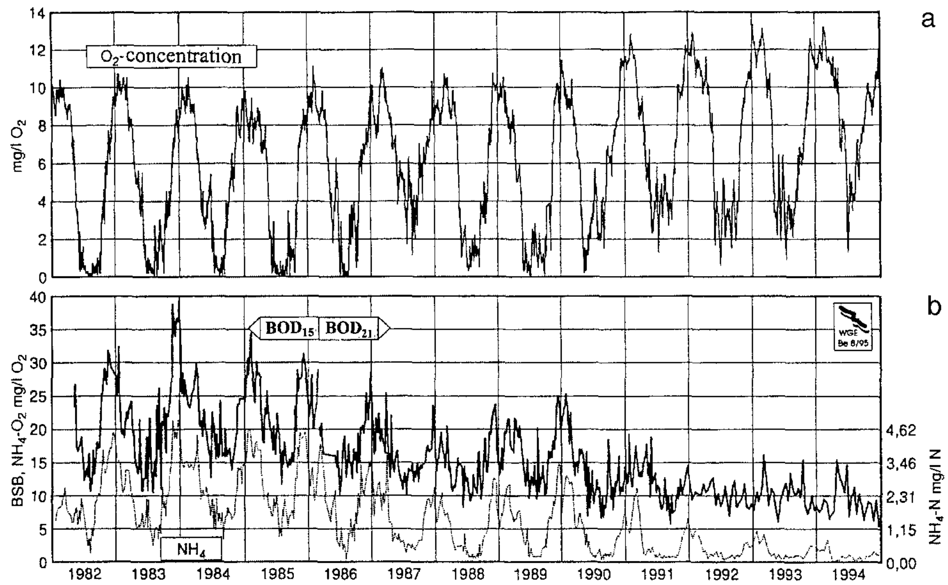

Fig. 2. Daily minimum concentrations of dissolved oxygen from continuous measurements in the Elbe Estuary at km 628.8 (**a**). For the same station BOD_{15}/BOD_{21} values and ammonium concentrations are shown determined at weekly intervals (**b**). The scale of the BOD-axis was magnified by a factor of 4.33 relative to the NH_4-N axis so that oxygen consumption during nitrification of ammonium can directly taken from the BOD-axis (from BERGEMANN et al. 1996).

BOD_{21} thereby decreased from up to 600,000 t a^{-1} before 1989 to below 200,000 t a^{-1} during 1994. High BOD values always corresponded with high concentrations in dissolved ammonium, suggesting that oxygen consumption coupled to nitrification might be an important process for total oxygen consumption. Likewise, ammonium was found to decrease together with decreasing oxygen concentrations in the Elbe (BERGEMANN et al. 1996). Given that all the ammonium present at the entrance of the estuary was nitrified, nitrification could account for about 45% of total oxygen consumption until 1989 but decreased thereafter to below 15% (Fig. 2b). Including a release of ammonium during degradation of organic matter, KERNER et al. (1995) calculated that after 1992 nitrification accounted for a maximum of about 25% of the total oxygen consumption below Hamburg Harbour during summer. Summarizing the results shown above it can be concluded that although the substrates for heterotrophic and autotrophic oxidation markedly decreased after the German reunion, they still were high enough to produce oxygen deficiencies in the Elbe Estuary. Likewise, we postulated for the field studies done in an interdisciplinary cooperation between 1992 and 1994 that an organic pool must be present that is low in concentration but easy to degrade, thus producing a high oxygen consumption within the regions of Elbe Estuary where oxygen deficiencies occur.

Phytoplankton was found to be an appropriate organic substrate which is transported from upstream reagions into the Elbe Estuary, dies and becomes microbially degraded during its transport through the Hamburg Harbour (WOLFSTEIN & KIES 1995). Phytoplankton biomass expressed in chlorophyll *a* did not decrease in the years after 1989 (Fig. 3). In contrast, during summer 1991 and 1992 chlorophyll *a* concentrations entering the estuary were markedly increased compared to the years before. This is explained by the reduction of pollution with toxic substances and an improvement of the light conditions in the upstream regions which both favour primary production (REINCKE 1992). Thus, phytoplankton as a pool of organic substrates for oxygen consumption processes remained sufficiently high to induce oxygen deficiencies even after 1989. That the phytoplankton decay caused oxygen deficiencies in the Elbe Estuary in 1993 was evident from the results of longitudinal measure-

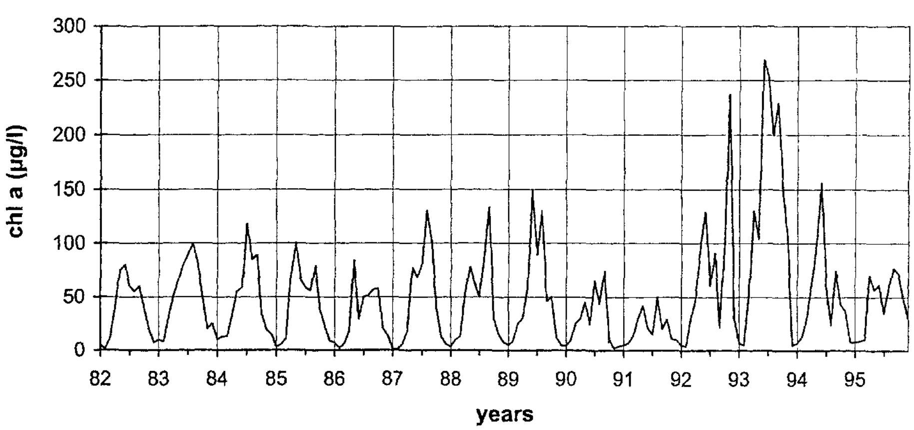

Fig. 3. Changes in phytoplankton biomass entering the Elbe Estuary in the period between 1982 and 1995 shown as chlorophyll *a* concentrations at km 590 determined at weekly intervals (data from ARGE 1982–95).

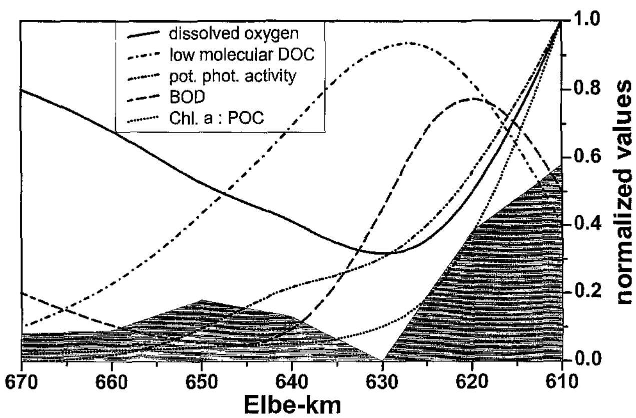

Fig. 4. Changes in the O_2 concentrations, low molecular weight dissolved organic matter (DOC), potential photosynthetic activity, biological oxygen demand (BOD_1) and composition of particulate matter along a longitudinal profile of the Elbe Estuary during a situation of oxygen deficiency in May 1993. The changes in the water depth along the profile (km 630 = 9.6 m) are illustrated by the shaded area.

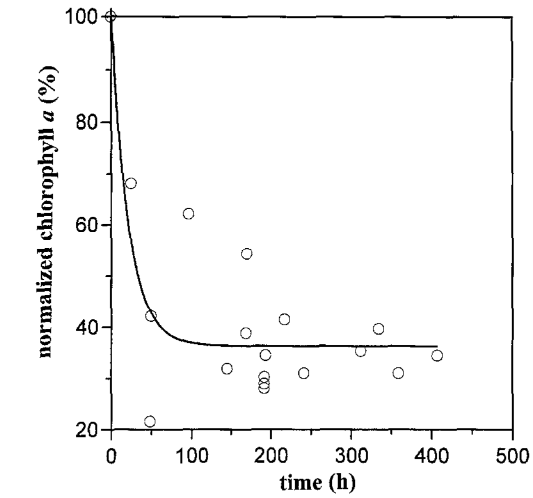

Fig. 5. Aerobic degradation of chlorophyll *a* in aggregated seston from the Elbe Estuary. The curve calculated by the least square method from the data points has the formula:
Chl. $a = 65.14 \times e^{-0.046 \times t} + 36.3$ ($r^2 = 0.696$, n = 15).

ments within the region of an oxygen minimum shown in Fig. 4 after normalization to dimensionless numbers between 0 and 1. The decrease in dissolved oxygen concentrations between km 610 and 630 was coupled to a decrease in POC concentrations and C:Chl *a* ratios suggesting that labile phytoplankton-born DOC was a preferred substrate for heterotrophic processes (Fig. 4). Within the same region the potential photosynthetic activity markedly decreased due to light limitation with increasing depth supporting that fresh phytoplankton was degraded. Degradation produced a maximum in oxygen consumption (BOD) within the region of the oxygen minimum zone. Concomittantly there was a maximum in the concentrations of low molecular weight dissolved organic substances (DOC) which could be used as a substrate in the oxygen consumption processes. These DOC compounds were produced mostly in anaerobic processes within seston aggregates.

Short term degradation of phytoplankton

An open question that arises from the results is the short term availability of the phytoplankton as a substrate in heterotrophic processes. Assuming that the transport of the SPM along the longitudinal profile of the Elbe Estuary was similar to the movement of the water mass, decomposition processes of the phytoplankton must have been completed within 2-4 days (BERGEMANN et al. 1996). This period is much shorter than the 20 to 30 days found for the degradation of most labile substances in estuarine phytoplankton detritus determined in static slurry incubations from oxygen consumption (HARGRAVE & PHILLIPS 1989). However, our laboratory experiments on seston from the Elbe Estuary presented here confirmed the field results and revealed that about 60% of the chlorophyll *a* was degraded within 50 hours after formation of aggregates (Fig. 5). That the decrease in Chl *a* reflected rapid decomposition of the phytoplankton whithin seston aggregates was shown recently by changes in the amounts of single amino acids (KERNER & YASSERY 1997). Thus, the discrepancy between our field studies with literature might be explained from the fact that most of the degradation of particulate matter in the Elbe Estuary occurs within aggregates. This assumption was confirmed by the findings of other authors that seston aggregates occur abundant in the Elbe Estuary and reach up to 5 mm in diameter (see EISMA 1993).

Oxygen consumption within aggregates

To elucidate the dynamics of microbial consumption processes within seston aggregates from the Elbe Estuary these were studied in laboratory experiments using Clark-type O_2-sensitive microelectrodes. Thereby great changes in the oxygen consumption rates were observed with time after aggregation of seston and different rates were detected within different layers of the aggregate (Fig. 6). After aggregation oxy-

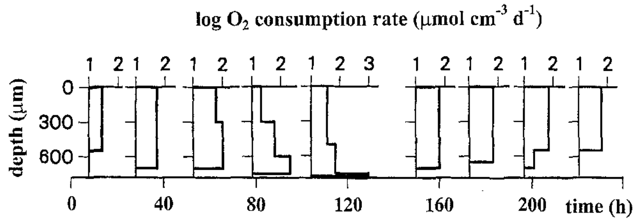

Fig. 6. Changes in oxygen consumption rates within a seston layer during different times after aggegation of material from the Elbe Estuary (from KERNER & GRAMM 1995).

gen consumption rates increased with time, and highest rates were found after about 70 hours. At the same time, anaerobic conditions occurred within the aggregate at a depth of about 650 µm. Further incubation was followed by a decrease in the oxygen consumption rates within the upper layers and oxygen was detected down to a depth of about 800 µm. It was then that great differences in oxygen consumption between different layers occurred with up to 1000 fold higher rates at the anaerobic-aerobic interface within the aggregate. A similar increase in the rates has often been described for deeper parts of sediments, explained by diffusion of reduced substances in anoxic depths into the anaerobic/aerobic interface and their chemical oxidation by dissolved oxygen (RASMUSSEN & JØRGENSEN 1992). In the present studies, this explanation was ruled out because respective substances such as Fe(II) and S(II) always remained below detection limit. In further studies we could show that dissolved organic substances produce the differences in the oxygen consumption within the aggregate (KERNER & EDELKRAUT 1995). These are produced by fermentation processes in the anaerobic part of the aggregate and are rapidly consumed after diffusion into aerobic layers. The DOC present in the Elbe Estuary for most of the year at concentrations of about 3 mg C l^{-1} might further enhance the oxygen consumption in the suspended aggregates in the field. Under these conditions anoxic seston aggregates are to expect a common phenomenon in the Elbe Estuary. This conclusion is supported by the laboratory study of PLOUG et al. (1997) using aggregates composed of phytoplankton detritus and fecal pellets incubated in a flow system. They found that at a bulk water oxygen concentration of 250 µM the lower limit for the oxygen respiration rate needed to create anoxia in the centre of 1 mm large aggregates was at 67 µmol O_2 cm^{-3} d^{-1}. This rate is below those determined in the seston aggregates of the Elbe Estuary for most of the time after aggregation (Fig. 6). It is therefore to conclude, that in the Elbe Estuary anoxic centres occur within seston aggregates of a diameter even of below 1 mm. In literature, the occurrence of anoxic microenvironments in oxygenated waters was first suggested from the detection of dissolved substances produced in anaerobic microbial processes (LAMONTAGNE et al. 1973; BROOKS et al. 1981; BURKE et al. 1983; CUTTER & KRAHFORST 1988). Using oxygen sensitive microelectrodes ALLDREDGE & COHEN (1987) determined anaerobic layers in large crustacean fecal pellets, and anoxic microzones were shown to allow sulfate reduction to occur within marine snow (SHANKS & REEDER 1993). The isolation of obligatory anaerobic bacteria from fresh zooplankton fecal pellets and sediment trap material gave further evidence that anoxia occurs within aggregates (BIANCHI et al. 1992; KARL & TILBROOK 1994; SIEBURTH 1993).

Regarding the cause of local oxygen deficiencies in the Elbe Estuary, the connection between cause and effect must now be revised with respect to the processes within seston aggregates. The simple linear connection deduced from the field experiments was that the availability of phytoplankton as a substrate in heterotrophic processes allowed microbial degradation processes at rates to produce oxygen deficiencies. Including processes within aggregates, the availability of organic substrates still regulates oxygen consumption. However, a decrease in oxygen concentrations within the seston aggregate produces reduced redox conditions, which now lead to an increased release of low molecular weight DOC compounds. The latter become available as organic substrates in oxygen consumption processes. Seston aggregates can therefore function as autocatalytic systems that should be taken into account in future studies on cycling of matter in aquatic environments.

Consequences for strategies to prevent oxygen deficiencies

The most effective way to control oxygen deficiencies produced by a secondary pollution, i.e. phytoplankton, is the reduction of the primary pollution. Because a reduction in the pollution might include concentrations of toxic substances and particulate matter primary production might even become enhanced when nutrients are not limiting growth. Therefore, management strategies should focus on a drastic reduction of both nitrogen and phosphorus.

Aggregation of the particulate material has been shown herein to have an autocatalytic effect on degradation processes, and degradation of phytoplankton within aggregates might be completed within a few days coupled to a respective oxygen demand. In estuaries, there is probably a complex interaction between flocculation induced by turbulence, differential settling, Brownian motion and organisms. Salinity was not found to influence the floc size distributions (EISMA et al. 1991). Therefore, aggregation is difficult to predict and control but might produce local and/or short term events of oxygen deficiencies in estuaries even at low particulate organic matter concentrations. Coupled to this, when toxic substances such as trace metals are present in the organic matter, these become released (KERNER & GEISLER 1995) which might have an deteriorating effect on the living conditions of the organisms in the open water.

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